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COBALT-BASE ALLOYS FOR SPACE-POWER SYSTEMS

[1963] ~~9 p. refs~~

N64 13351*

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Repr. from J. Metals, Dec. 1963 p 1-8 refs
(NASA RP-116)

The high-temperature strength and ductility of cobalt - refractory-metal alloys designed for advanced turboelectric space-power systems were investigated. An average life of over 200 hr was obtained at 1800°F and 15,000 psi with the strongest alloy, Co-25W-1Ti-1Zr-0.4C. Workability of the stronger alloys was demonstrated by rolling.

Cobalt-base alloys are being used extensively for many high-strength, high-temperature applications, and research is underway in various organizations to extend their capability. Among the research programs that have been conducted with cobalt-base alloys are investigations of binary and ternary systems in which refractory metals such as tungsten, molybdenum, columbium, and tantalum, as well as other metals, were added to a cobalt base.[1-5] These investigations indicated that cobalt - refractory-metal systems have considerable potential for achieving high strength at high temperature. In particular, the investigators of Ref. 2 showed that the ternary compositions Co-25W-0.25C and Co-25W-5Cr had stress-rupture properties which approached those of L-605 (HS-25), a strong, currently used, cobalt-base alloy. Although cobalt - refractory-metal alloys would not be expected to have the high oxidation resistance of the chromium and aluminum-bearing superalloys, there are important space-age applications, such as advanced power systems for space vehicles, where oxidation resistance is not a requirement and where the cobalt - refractory-metal alloys could be advantageously employed.

Turboelectric systems, in which nuclear power is converted to electric power through the medium of a closed thermodynamic cycle, are among the most promising systems under development both for propulsion and for auxiliary power in space vehicles.[6] Such systems consist of many components, including the reactor, radiator, ducting, and various turbogenerator components. Many materials problems must be overcome to meet the design requirements of such a power system.

The ducting and radiator components pose some of the most critical materials problems. The alloys used must be ductile so that they may be readily formed. Since welded components are required for the radiator, the alloys should have adequate strength in the as-welded or welded and stress-relieved condition.

In addition to high temperatures, the external surfaces of the ducting and the radiator will be exposed to the vacuum environment of space. It has been shown with several current high-temperature alloys that appreciable weight loss is incurred upon heating in a relatively low vacuum of 10^{-3} mm Hg.[7] At 1740°F, which is in the temperature range of interest for turboelectric space-power systems, a maximum weight loss of 5% would be expected with one of these alloys after only 18 hr of exposure. Upon long-time (10,000 hr) exposure in the much higher vacuum of space, it is conceivable that structural degradation of materials could occur as a result of the loss of highly volatile alloying constituents. Consideration of the evaporative loss rates of various metals indicates that cobalt has a relatively low evaporation rate, considerably lower than nickel or iron.[8] The refractory metals, as well as titanium, zirconium, and carbon, have still lower loss rates. Although the refractory metals have the lowest evaporation rates, they are generally difficult to form, require extensive protection against oxidation in ground testing, and are expensive. Therefore, as an economical means of reducing the danger of material deterioration from evaporation, cobalt-base alloys with refractory metals as the primary alloying constituents would appear to be promising. Currently available cobalt- and nickel-base alloys, on the other hand, contain high percentages of chromium and/or aluminum, both of which have high evaporation rates.

The internal surfaces of the radiator and allied ducting will be exposed to the corrosive action of the heat-transfer and turbine-drive fluids. The severity of corrosion will be directly related to the fluid used, which, in turn, depends upon the thermodynamic cycle. The fluid can be an inert gas such as argon, in which case corrosion will not be a problem. It can also be a liquid metal such as mercury or the alkali metals. Liquid metals are favored in current designs. Extensive corrosion studies made at the NASA with mercury up to 1300°F for 1000 hr have shown nickel-free cobalt-base alloys to be superior to nickel-base alloys and to nickel-bearing cobalt-base alloys (unpublished data obtained at Lewis Research Center), although inferior to the refractory metals and iron-base al-

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loys (except those containing large percentages of soluble elements such as manganese and chromium). Limited data from capsule tests with potassium at 1600°F indicate that a cobalt-base alloy has better corrosion resistance than a nickel-base alloy.[9] Extensive research is still required to fully establish the relative merits of various materials with respect to alkali liquid-metal corrosion.

The need for good magnetic properties and high strength at elevated temperatures in generator rotors constitutes another major materials problem. In order not to consume energy in cooling, it is desirable for electrical generators to operate at 1500°F or above. High magnetic permeability is required to obtain efficient electric power generation. High strength is needed because of the high rotational stresses. Cobalt has the advantage of having a very high Curie temperature (2068°F), considerably higher than either iron (1418°F) or nickel (676°F). The cobalt - refractory-metal alloys appear to have potential for both high Curie temperature and high-temperature strength.

There are, therefore, a number of major reasons why cobalt - refractory-metal alloys should be investigated for service up to 2000°F in advanced space-power systems: (1) good high-temperature strength potential, (2) good fabricability potential, (3) low evaporation rates, (4) the advantage of utilizing production and fabrication capabilities developed over many years for superalloys as contrasted to the relatively new refractory-metal fabrication facilities, (5) relatively low cost as compared to refractory metals, and (6) potentially good magnetic properties at high temperatures.

Because of the potential of cobalt - refractory-metal alloys for advanced turboelectric space-power applications, an investigation was initiated at the NASA Lewis Research Center to provide improved alloys of this type with good high-temperature strength and sufficient ductility to make sheet. Exploratory melts of a number of cobalt - refractory-metal compositions were made. Experimental alloys were screened by stress-rupture tests at 1800°F and 15,000 psi. The most favorable composition was modified by systematic alloying additions. These modified alloys were all evaluated by stress-rupture tests and by tensile tests at room temperature and 1800°F. Workability of the stronger alloys was investigated by rolling.

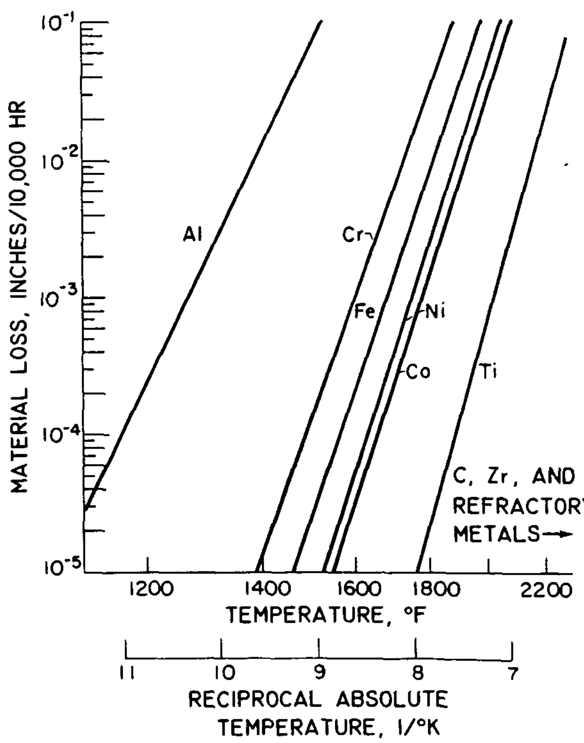


Fig. 1—Material loss in vacuum as a function of temperature for several metals.[8]

Investigation procedure

Alloys Investigated

Utilizing the research background made available by other investigators,[1-5] trial melts of various binary and ternary compositions that contained refractory metals as the major alloying constituents were made. The refractory metals were chosen because of their low evaporation rates in the temperature range of interest (1400° to 2000°F). Fig. 1 shows the calculated material loss in in. per 10,000 hr in vacuum as a function of temperature for several metals as compiled from Ref. 8. It should be noted that these calculations were made for unalloyed metals and that dilution and other effects would undoubtedly occur in complex alloys.

Samples from the trial melts were screened for high-temperature strength and for ductility by stress-rupture tests and swaging. A ternary alloy, Co-25W-1Ti, was selected as the basis for systematic alloying studies. This alloy was also shown to be one of several Co-W alloys with promising high-temperature strength properties in Ref 2. The Co-25W-1Ti alloy was modified by systematic additions of two other elements, carbon and zirconium, which have extremely low evaporation loss rates. The quantities of the additions considered are apparent from the listing of the nominal compositions investigated (Table I). All additions were made by adjusting (i.e., subtracting from) the cobalt content.

Chemical Analysis

Randomly selected heats of the compositions investigated were chemically analyzed by an independent laboratory. The results of these analyses are shown in Table I. Some losses in charging elements, particularly zirconium, titanium, and carbon, occurred during melting and casting. In order to minimize such losses, an inert gas (argon) cover was employed. Although this cover was used over the crucible during the entire heating and melting cycle, it could not be entirely effective in excluding air from the crucible. As might be expected, the loss of carbon was greater at the higher concentrations. For example, for an addition of 0.60% C, an analysis of 0.50% C was reported; for an addition of 0.10% C, 0.096% C was reported. While some loss of both titanium and zirconium was expected, it was not anticipated that the loss of zirconium would be so much greater than that of titanium. The greater negative free-energy-of-formation value for zirconium oxide compared to that of titanium oxide may explain this greater loss of zirconium.

Casting and Inspection Techniques

The casting procedure was similar to that used in nickel-base alloying studies made at the NASA and is described in detail in Refs. 11 and 12. Briefly,

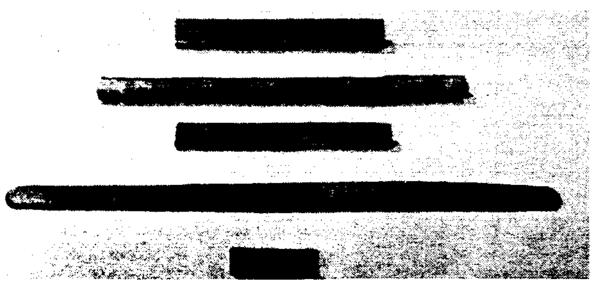


Fig. 2—Steps in making Co-25W-1Ti-0.4C sheet from cast rounds. From top: cast ½-in. round; swaged 0.430-in. round; rolled 0.360-in. square; rolled 0.625x0.060-in. strip.

a 50-kw, 10,000-cps, water-cooled induction unit was used in melting. All melts were made in stabilized zirconia crucibles under a blanket of commercially pure argon. The charges consisted of electrolytic cobalt, ground tungsten rod, sponge titanium and zirconium, and carbon black which had previously been compressed into briquettes. Pouring temperature, which was measured with an optical pyrometer, was 3100°±50°F. All castings were statically poured without inert gas protection into silica investment molds heated to 1600°F. The molds were allowed to cool to room temperature before the investment was removed.

The lost-wax process was used to make molds of stress-rupture and tensile test bars as well as the blanks used for workability studies. The stress-rupture and tensile bars had conical shoulders and a gage section ¼ in. in diameter and 1⅜ in. long. The blanks used for workability tests were rounds nominally ½ in. in diameter and 3 in. long. All test bars and blanks were radiographed. They were then inspected either with fluorescent penetrant dye or visually at a magnification of 10.

Stress-Rupture and Tensile Tests

Cast specimens of all alloys were stress-rupture tested in air, and some of the cast alloys were also tested in dried commercially pure helium at atmospheric pressure. All sheet stress-rupture specimens were solution treated and were tested in helium in order to prevent excessive loss of metallic specimen cross section in long-time tests; this was considered desirable for the thin (0.050 in.) sheet specimens employed.

All tensile tests were run in air. Because of the short duration of these tests, it was not considered necessary to provide an inert gas atmosphere.

Workability

The workability of the stronger alloys was investigated by making sheet from investment-cast bars and by tensile tests of the sheet. The progressive steps in making sheet from investment cast blanks of alloy Co-25W-1Ti-0.4C are shown in Fig. 2. Nominally ½-in. cast rounds were heated in air to 2150°F and swaged to a diameter of 0.430 in. Four successively smaller dies having openings of 0.538, 0.492, 0.460, and 0.430 in. were used. The swaged bars were subsequently rolled to squares approximately 0.360 in. on an edge. These rough squares were then hot rolled to sheet approximately 0.060 in. thick. The stock was heated to 2150°F between each pass, and the reduction per pass was about 0.030 inch.

A similar procedure was used for making sheet from alloy Co-25W-1Ti-1Zr-0.4C. However, hot-pressing was substituted for swaging as the initial

Table I. Alloy Compositions

Alloys Investigated	Actual Composition of Typical Heats, wt % Co	W	Ti	Zr	C
Co-25W-1Ti	74.31	24.95	0.54	ND[a]	0.022
Co-25W-1Ti-0.1C	72.66	26.41	0.85	ND	0.096
Co-25W-1Ti-0.2C	72.62	26.05	0.90	0.01	0.17
Co-25W-1Ti-0.3C	72.43	26.42	0.92	ND	0.286
Co-25W-1Ti-0.4C	72.83	25.84	0.98	ND	0.334
Co-25W-1Ti-0.5C	bal.	24.19	0.99	—	0.44
Co-25W-1Ti-0.6C	bal.	24.24	1.06	—	0.50
Co-25W-1Ti-0.25Zr-0.4C	bal.	24.97	0.91	0.13	0.34
Co-25W-1Ti-1Zr-0.4C	bal.	24.18	1.17	0.51	0.42
Co-25W-1Ti-1.5Zr-0.4C	bal.	24.97	0.96	1.13	0.45
Co-25W-1Ti-2Zr-0.4C	bal.	25.00	0.97	1.41	0.43

Commercial Alloys[b]	Nominal Composition, wt % Co	Cr	Ni	W	Cb	Ta	Fe	Ti	B	Zr	C
WI-52	bal.	21	—	11	2	—	2	—	—	—	0.45
L-605 (HS 25)	bal.	20	10	15	—	—	1	—	—	—	0.10
HS 31	bal.	25	10	8	—	—	1.5	—	—	—	0.50
J-1650	bal.	19	26	12	2	—	—	4	0.02	—	0.2
SM 302	bal.	22	—	10	—	9	—	—	0.005	0.20	0.85

[a] Not detectable or less than 0.01.
[b] Data from Ref. 13.

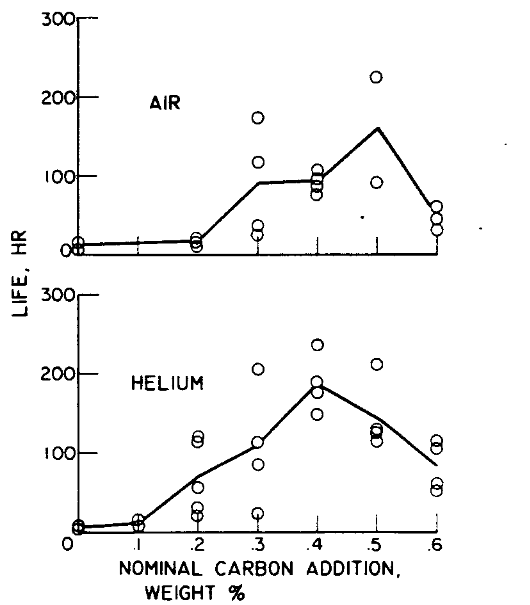


Fig. 3—Effect of carbon additions on rupture life of Co-25W-1Ti at 15,000 psi and 1800°F in as-cast condition, tested in air and in helium.

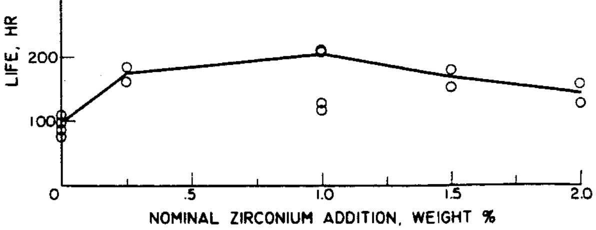


Fig. 4—Effect of zirconium additions on rupture life of Co-25W-1Ti-0.4C at 15,000 psi and 1800°F in as-cast condition.

step. The ½-in. cast rounds were pressed at 2150°F in a mechanical press to a thickness of ¼ in. From this point the procedure was the same. The flat bars were heated to 2150°F in air and hot rolled to 0.060-in. strip, using reductions of approximately 0.030 in. per pass.

Sheet strips of roughly 0.625x0.060 in. were obtained. Tensile specimens having a test section 1x 0.175x0.050 in. were machined from these strips.

Alloy evaluation results

Stress-Rupture Data

The effects of nominal carbon additions to alloy Co-25W-1Ti on stress-rupture life at 15,000 psi and 1800°F in the as-cast condition are shown in Fig. 3. Data were obtained in helium as well as in air. Straight lines connect the average life values obtained with each alloy. Additions of carbon of 0.3

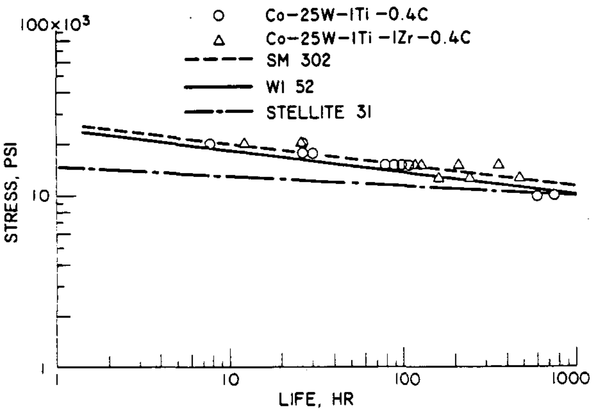


Fig. 5—Stress-rupture properties of several cast cobalt-base alloys at 1800°F in air.

to 0.5% resulted in the greatest increases in life. In air, average rupture life was increased from approximately 12 hr for the zero-carbon alloy to 160 hr for the 0.5%-carbon alloy (Fig. 3). In helium, average rupture life was increased even more, from approximately 4 hr for the zero-carbon alloy to 190 hr for the 0.4%-carbon alloy (Fig. 3).

Maximum rupture lives greater than 200 hr were obtained both in air and in helium as a result of carbon additions. The long lives obtained with these alloys in air made it apparent that a valid stress-rupture evaluation of the cast alloys in this series could be obtained without the use of an inert atmosphere. Of the several carbon-modified alloys, the Co-25W-1Ti-0.4C alloy was selected for further investigation because of its high stress-rupture properties and its excellent workability which will be discussed later.

The effects of nominal zirconium additions on the rupture life in air at 15,000 psi and 1800°F of as-cast alloy Co-25W-1Ti-0.4C are shown in Fig. 4. Again, straight lines were drawn between the average rupture life values obtained with each alloy. There is no well-defined peak value. The average stress-rupture life was increased from 94 to 205 hr and a maximum life of 355 hr was obtained by making zirconium additions.

Fig. 5 compares the stress-rupture properties in air of two alloys—Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C—in the as-cast condition, with several of the strongest current cast cobalt-base alloys. The commercial alloy data were obtained from Ref. 13 and from Haynes Stellite data sheets. It is evident that, even though no attempts were made to protect the Co-W alloys of this investigation against oxidation by coatings, the lives of these alloys in air compare favorably with those of Stellite-31, WI-52, and Sierra alloy 302. The latter three alloys achieve oxidation resistance from large amounts of chromium (25, 21, and 22%, respectively) which are present as alloying constituents.

To provide an indication of the capability of the Co-W alloys for long-time service at stress levels comparable to those expected in advanced space-power system ducting applications, limited stress-rupture tests are being conducted in helium at 5000 psi. Over 7000 hr have been accumulated to date on a test bar of alloy Co-25W-1Ti-0.4C at 1800°F at this stress. Because of obvious limitations with respect to test equipment and the length of time involved, only a few such runs are being made.

A comparison of the stress-rupture properties of solution-treated sheet of alloy Co-25W-1Ti-0.4C and of two current cobalt-base sheet alloys, L-605 (HS-25) and J-1650, is presented in Fig. 6. The Co-W alloys were tested in helium. The commercial alloy data from Ref. 13 and Haynes Stellite data sheets were obtained in air. Although only limited data have been obtained with the Co-W alloys to date, these data compare favorably with data for the commercial alloys. Solution treatments were the only heat treatments attempted with Co-W alloys.

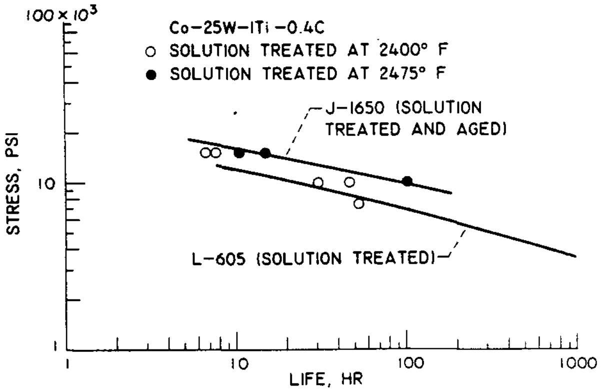


Fig. 6—Stress-rupture properties of Co-25W-1Ti-0.4C alloy sheet at 1800°F in helium compared to current cobalt-base sheet alloys.

It is probable that the properties could be improved by suitable aging or combinations of working and aging treatments. Further investigation is required in order to develop satisfactory procedures of this type.

Tensile and Hardness Data

The effect of nominal carbon additions on the tensile properties of cast alloy Co-25W-1Ti at room temperature and 1800°F is shown in Fig. 7. Straight lines were drawn through the average strength and ductility values obtained with each alloy. At room temperature (Fig. 7[a]) an apparent minimum in strength occurred at a 0.1%-nominal carbon content. Ultimate strength decreased from an average value of 107,300 psi for the zero-carbon alloy to 78,000 psi for the 0.1%-carbon alloy. As carbon content was further increased, ultimate strength gradually increased to an average value of 105,000 psi at a 0.6%-nominal carbon content. At 1800°F

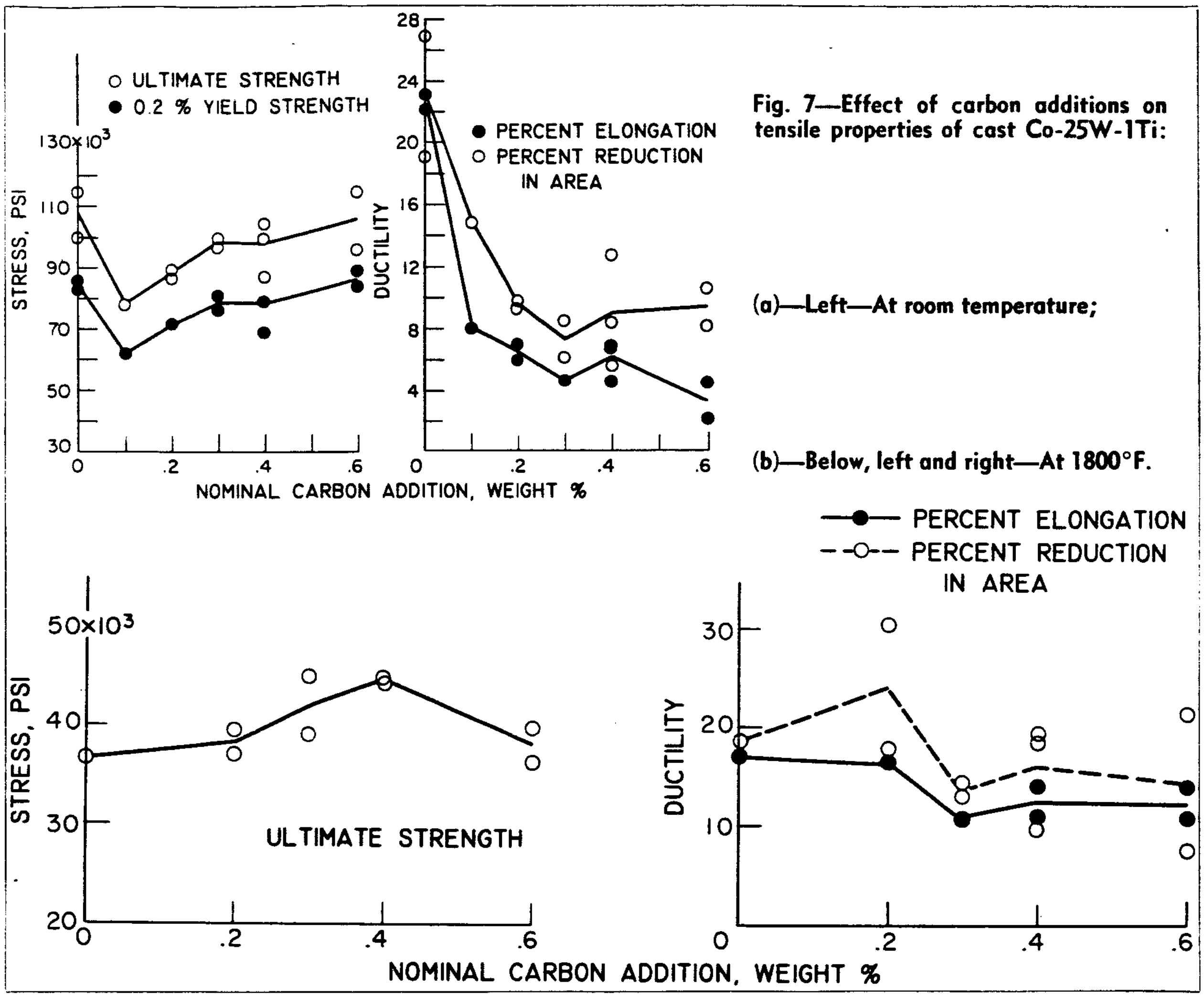


Fig. 7—Effect of carbon additions on tensile properties of cast Co-25W-1Ti:

(a)—Left—At room temperature;

(b)—Below, left and right—At 1800°F.

(Fig. 7[b]) the zero-carbon-content alloy had less strength than any of the carbon-modified alloys. The highest average ultimate tensile strength of 44,500 psi was obtained with alloy Co-25W-1Ti-0.4C. It will be recalled that this alloy was also one of the strongest carbon-modified alloys on the basis of stress-rupture tests (Fig. 3). As might be expected, the ductility of the carbon-modified alloys generally followed a trend opposite to that of tensile strength, although considerable scatter in data tends to obscure this effect. It is interesting to note that alloy Co-25W-1Ti-0.4C retained a great deal of its strength at 1800°F. For example, comparison of the average ultimate tensile strength of alloy Co-25W-1Ti-0.4C at room temperature and at 1800°F indicates that its strength at the latter temperature is approximately 46% of its room-temperature strength. Elongations of 6 and 12% at room temperature and 1800°F, respectively, were obtained with alloy Co-25W-1Ti-0.4C. Its ductility was sufficient so that it could be formed into sheet.

Table II presents data for sheet material. In the rolled condition, a maximum room-temperature ultimate strength of 209,800 psi and a 25% elongation were obtained with this alloy. Strength and ductility in the annealed condition were also high both for alloy Co-25W-1Ti-0.4C and for the strongest (on the basis of hot-tensile tests) zirconium-modified alloy, Co-25W-1Ti-1Zr-0.4C. At 1800°F, maximum ultimate strengths of 37,600 and 38,400 psi as well as 15 and 22% elongations, respectively. were obtained with these alloys. The maximum Rockwell hardness of alloys Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C was C-48 and was obtained in the as-rolled condition; this compares to as-cast hardnesses of C-29.5 and C-32, respectively. After rolling and a 2400°F solution treatment, both alloys had a hardness of approximately C-28. By raising the solution treating temperatures to 2475°F, the hardness of alloy Co-25W-1Ti-0.4C was reduced to C-17.

Workability

One of the strongest carbon-modified alloys, alloy Co-25W-1Ti-0.4C, was readily formed into sheet. The workability of the 0.2% carbon-modified alloy was also investigated, and it too was readily formed into sheet. As described previously, the initial step in working was to swage cast bars. No cracks were observed in either of these alloys after the swaging. However, the alloys containing zirconium cracked during swaging. Cracking was more pronounced with increased zirconium content. By substituting hot pressing for swaging as the initial working step, these alloys were also readily made into sheet. Dressing was occasionally required to remove edge cracking which occurred during rolling with the zirconium-modified alloys, whereas the alloys without zirconium were almost entirely free from edge cracking and did not require dressing.

Table II. Summary of Sheet Tensile Data

Alloy	Condition[a]	Test Temperature, °F	Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, %	Reduction in Area, %
Co-25W-1Ti-0.2C	ST:2400°F, 16 hr	Room	81,500	154,500	30	21.2
Co-25W-1Ti-0.2C	ST:2400°F, 16 hr	Room	85,200	161,000	35	26.2
Co-25W-1Ti-0.4C	As-rolled	Room	130,400	199,000	20.3	22.0
Co-25W-1Ti-0.4C	As-rolled	Room	143,500	209,800	25.0	24.4
Co-25W-1Ti-0.4C	ST:2475°F, 16 hr	Room	65,000	115,500	13.3	15.6
Co-25W-1Ti-0.4C	ST:2475°F, 16 hr	Room	60,200	96,500	15.6	18.2
Co-25W-1Ti-0.4C	ST:2400°F, 16 hr	Room	75,800	139,000	20.3	15.8
Co-25W-1Ti-0.4C	ST:2400°F, 16 hr	Room	77,900	149,500	20.3	16.8
Co-25W-1Ti-0.4C	ST:2400°F, 16 hr	1800	—	37,600	15	—
Co-25W-1Ti-0.4C	ST:2400°F, 16 hr	1800	—	32,000	16	—
Co-25W-1Ti-1Zr-0.4C	ST:2400°F, 16 hr	Room	76,900	150,300	23	17.8
Co-25W-1Ti-1Zr-0.4C	ST:2400°F, 16 hr	Room	79,600	143,750	18	12.5
Co-25W-1Ti-1Zr-0.4C	ST:2400°F, 16 hr	1800	—	38,100	17	—
Co-25W-1Ti-1Zr-0.4C	ST:2400°F, 16 hr	1800	—	38,400	22	—

[a] Solution treatments performed in argon, followed by water quench.

In room-temperature tensile tests, elongations up to 35, 25, and 23% were obtained with sheet specimens of alloys Co-25W-1Ti-0.2C, Co-25W-1Ti-0.4C, and Co-25W-1Ti-1Zr-0.4C, respectively (Table II). These elongations indicate that further forming operations are possible with these alloys. This is, of course, necessary for the fabrication of radiator components and ducting in advanced space-power system applications.

Metallographic Studies

Fig. 8 shows a photomicrograph of alloy Co-25W-1Ti-0.4C at 250X. Carbide particles appear as a noncontinuous interdendritic network. There were a limited number of idiomorphic microconstituents, probably TiC or TiCN, present.

A Widmanstätten structure was observed. A microconstituent with a similar appearance was identified (Ref. 1) as W_2Co_7 precipitate in a matrix of β fcc solid solution in the alloy Co-35W, heated for 50 hr at 1832°F. The phase W_2Co_7 has been identified as WCo_3 by later investigators.[14] In current notation, the fcc solid solution is designated as α rather than as β.[14] The investigators of Ref. 2 referred to a similar structure found in a Co-25W binary alloy aged for 256 hr at 1652°F as *Widmanstätten* ϵ.

Fig. 9 shows a photomicrograph (250X) of the as-cast alloy Co-25W-1Ti-1Zr-0.4C. There is no evidence of a Widmanstätten structure. The appearance of the interdendritic carbide network has been modified by the addition of zirconium.

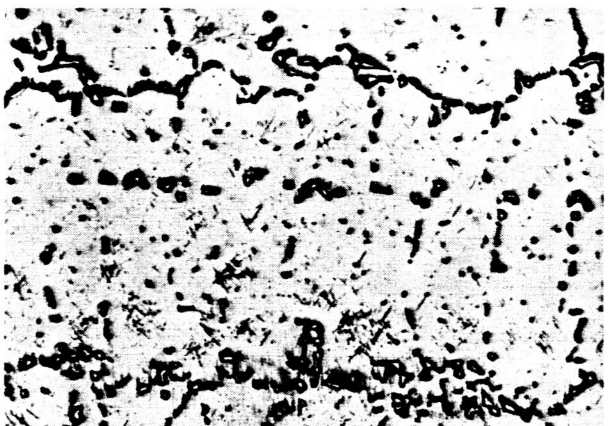


Fig. 8—As-cast microstructure of Co-25W-1Ti-0.4C. 250X.

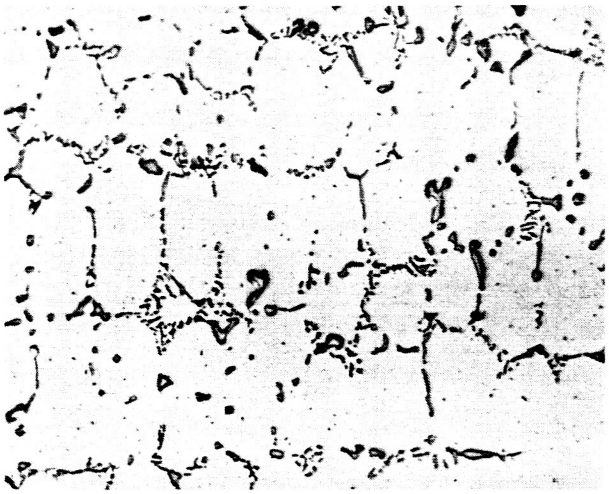


Fig. 9—As-cast microstructure of Co-25W-1Ti-1Zr-0.4C. 250X.

Photomicrographs at 250X of alloy Co-25W-1Ti-0.4C after working are shown in Fig. 10. The changes in microstructure brought about by rolling at 2150°F are apparent from Fig. 10(a). The microconstituents have been stringered by the working process, and there is evidence of twinning.

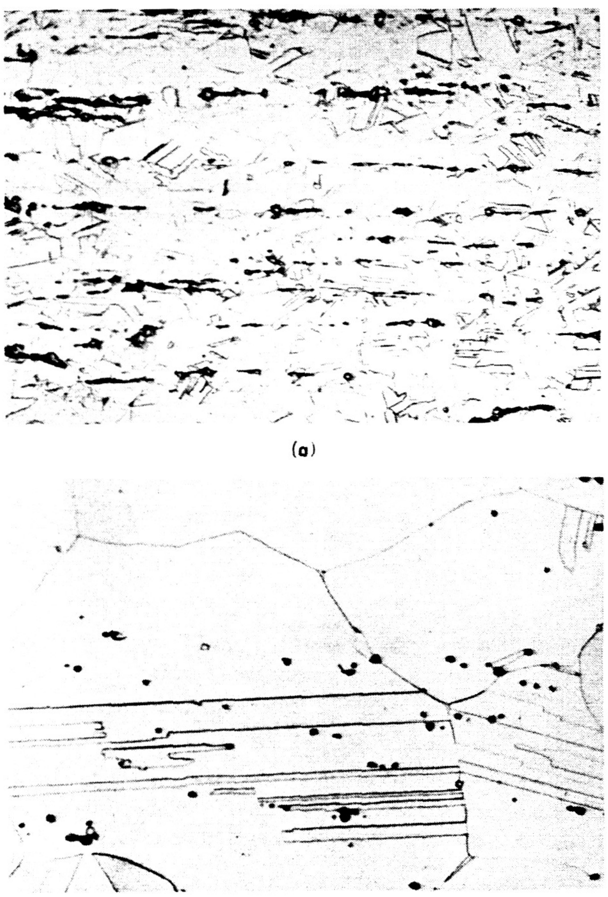
Fig. 10(b) shows the rolled alloy after a 16-hr solution heat treatment at 2400°F. This heat treatment dissolved virtually all of the minor phases, although some of the carbonitrides were not dissolved. Some etch pits, which are similar in appearance to carbides, are present in the specimen.

Samples from cast alloy Co-25W-1Ti-0.4C before and after stress-rupture testing, as well as from solution treated Co-25W-1Ti-0.2C alloy sheet, were examined by X-ray diffraction. In all the samples, the matrix was shown to be a fcc solid solution of α Co. The possible presence of the intermetallic compound Co_3W was noted in the as-cast 0.4% carbon-modified alloys, while none was detected in the solution-treated sheet. Only limited evidence of the presence of the ϵ Co phase was obtained for all the samples. There was no clear evidence of the MC type of carbides, although their presence would be expected.

Concluding remarks

Although much additional information must be obtained in order to describe fully the properties of this alloy series, the data presented indicate that it has considerable potential for turboelectric space-power system applications. Because the alloys contain only low-vapor-pressure alloying constituents, they are inherently more resistant to evaporation in a space environment than superalloys that contain chromium and aluminum. The excellent high-temperature strength of these Co-W alloys compares favorably with current cobalt-base alloys. The Co-W alloys also have been shown to have excellent workability. Subject to their ability to withstand corrosion by the heat-transfer fluids, these alloys appear attractive for ducting and turbine components of turboelectric space-power systems. The combination of potential high Curie temperature and high-temperature strength makes this alloy system also appear attractive for electrical generating components of these systems.

In order to exploit the potential of these alloys, it is suggested that additional research be conducted. In particular, additional long- and short-time strength data in high vacuum as well as in helium must be obtained for sheet material, and weldability as well as possible effects of welding upon sheet properties must be investigated. The possibility of embrittlement caused by long-time use at high temperatures should be investigated. Also, the potential benefits of heat treatment or combined working and heat treatment on strength should be explored. Resistance to alkali metal corrosion above 1300°F must be investigated more fully, and protective coatings should be considered as a means of extending the use of these alloys to service in air. Finally, the magnetic properties at high temperatures should be determined, in order to evaluate these alloys for applicability to the electrical generating equipment. In all of these areas, additional alloying approaches should be considered to optimize material properties.



(a)

(b)

Fig. 10—Microstructure of Co-25W-1Ti-0.4C sheet, longitudinal section; (a) as rolled, (b) solution treated at 2400°F. 250X.

Summary

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The following major results were obtained from an investigation to provide cobalt-base alloys for application to advanced turboelectric space-power systems:

1) A series of cobalt-base alloys was developed which utilized only elements with extremely low evaporative-loss rates as alloying constituents in order to minimize possible structural deterioration by evaporation of volatile constituents in space applications.

2) This alloy series compares favorably in high-temperature strength in both the as-cast and wrought condition with the strongest current cobalt-base alloys. Average rupture lives of 94 and 205 hr were obtained in the cast condition at 15,000 psi and 1800°F in air with two of the strongest alloys, Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C, respectively. A maximum rupture life of 100 hr was obtained at 10,000 psi and 1800°F in helium with solution-treated sheet made from the former alloy.

3) The strongest high-temperature alloys in this series, Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C, were readily formed into sheet by hot rolling. Maximum elongations of 25 and 23% respectively, were obtained in room-temperature tensile tests with sheet specimens of these alloys. These results suggest that these alloys could be fabricated into ducting and radiator components for advanced turboelectric space-power systems.

4) Although oxidation resistance is not a requirement in space-power system applications, results of long-time stress-rupture tests in air suggest that only limited oxidation protection would be required in ground-proof tests of space-system components made from these alloys.

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